Double cusp: Model prediction and observational verification

Simon Wing, Patrick T. Newell, and J. Michael Ruohoniemi
The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland

Abstract. Recent modeling of the entry of solar wind plasma into the magnetosphere and ionosphere has adequately simulated the large-scale particle precipitation features in the observed cusp, mantle, polar rain, and open-field line low-latitude boundary layer regions. The assumption of a simple dawn–dusk electric field limited the models to the near-noon region and southward interplanetary magnetic field (IMF) case. Here, we present an improved model that incorporates the electric field obtained from statistical convection patterns. When the IMF is strongly duskward/dawnward and weakly southward, the model predicts the occurrence of a double cusp near noon: one cusp at lower latitude and one at higher latitude. The lower-latitude cusp ions originate from low-latitude magnetosheath, whereas the higher-latitude ions originate from the high-latitude magnetosheath. The lower-latitude cusp is located in the region of weak azimuthal \( \mathbf{E} \times \mathbf{B} \) drift, resulting in a dispersionless cusp, as would be observed from a typical meridional trajectory of a polar-orbiting satellite. The higher-latitude cusp is located in the region of strong azimuthal and poleward \( \mathbf{E} \times \mathbf{B} \) drift. Because of a significant poleward drift, the higher-latitude cusp dispersion has some resemblance to that of the typical southward IMF cusp. This prediction was subsequently confirmed in a large case study with Defense Meteorological Satellite Program (DMSP) data. Occasionally, the two parts of the double cusp have such narrow latitudinal separation that they give the appearance of just one cusp with extended latitudinal width. From the 40 DMSP passes selected during periods of large (positive or negative) IMF \( B_y \) and small negative IMF \( B_y \), 30 (75%) of the passes exhibit double cusps or cusps with extended latitudinal width. The double-cusp result is consistent with the following new statistical results: (1) the cusp latitudinal width increases with \( |\text{IMF} B_y| \) and (2) the cusp equatorward boundary moves to lower latitude with increasing \( |\text{IMF} B_y| \).

1. Introduction

An important part of the dayside solar wind–magnetosphere interaction is magnetic merging or reconnection. A classical picture of this model was presented by Dungeons [1961], where a purely southward interplanetary magnetic field (IMF) and northward magnetospheric magnetic field near the subsolar magnetopause merge. As a result, the shocked solar wind particles can and do enter the magnetosphere, and some precipitate into the ionosphere. Although these particles originate in the solar wind, once they have entered the magnetosphere and ionosphere, they exhibit distinctly different characteristics in energy, density, and temperature at different local times and latitudes. Observations at low altitude show that the resulting particle precipitation in the open-field line can generally be classified into four regions (ordered from low to high latitude for a typical southward IMF case): open-field low-latitude boundary layer (LLBL), cusp, mantle, and polar rain [e.g., Newell et al., 1991b; Newell and Meng, 1995; Onsager and Lockwood, 1997]. The main physical processes that give rise to these four regions have been generally understood [e.g., Rosenbauer et al., 1975; Hardy et al., 1975, 1979, 1986; Shelley et al., 1976; Schopke et al., 1976; Hill and Reiff, 1977; Haerendel et al., 1978; Lundin, 1988; Cowley and Owen, 1989; Newell et al., 1989, 1991a; Lyons et al., 1994; Xu et al., 1995] and have even been modeled successfully [e.g., Onsager et al., 1993; Wing et al., 1996; Xue et al., 1997; Newell and Wing, 1998; Delcourt et al., 2000]. Of these four regions, partly because of its higher flux and energy and partly because of its theoretical importance, the cusp was discovered first [Eather and Mende, 1971; Heikkinen and Winningham, 1971; Frank, 1971] and has attracted the most attention.

In the antiparallel merging model, the local magnetic shear determines when and where merging occurs [e.g., Crooker, 1979]. In this model, merging occurs at the low-latitude magnetopause when the IMF is substantially southward but moves to higher latitudes for other IMF orientations [e.g., Crooker, 1979; Rodger et al., 2000]. Because of its proximity to the open/closed boundary, the particle cusp has been used to infer the merging site, albeit with some ambiguity [e.g., Menietti and Burch, 1988; Woch and Lundin, 1992; Lockwood and Smith, 1992; Newell et al., 1995]. Many studies used cusp observations to infer merging sites that are consistent with the antiparallel model for various southward and northward orientations of IMF, namely, at low latitudes and high latitudes, respectively [e.g., Hill and Reiff, 1977; Reiff et al., 1977; Burch et al., 1982; Carlson and Torbert, 1980; Lockwood and Smith, 1992; Woch and Lundin, 1992]. However, other cusp studies presented evidence for low-latitude reconnections or simultaneous high- and low-latitude reconnections even for periods of north-
ward IMF [e.g., Øieroset et al., 1997; Chandler et al., 1999; Fuselier et al., 2000]. The entry points of cusp particles and cusp morphology during periods of duskward or dawnward IMF have not been investigated in detail. Studies with in situ measurements at the magnetopause reported that in the vicinity of the subsolar region, merging occurs at modest magnetic field shear, ranging from 60° to 180°, but at locations away from the subsolar region at larger shear, apparently >135° [e.g., Gosling et al., 1990, 1991]. The merging locations during periods when the IMF is dominated by its y component, whether at high or low latitudes or simultaneously at both latitudes, should have significant impacts on the cusp particle source regions and have clear signatures in the cusp morphology.

The literature of the last three decades is rich with studies on the IMF control of the particle cusp properties, e.g., locations, energy-latitude dispersions, and longitudinal widths [e.g., Burch, 1972; Hill and Reiff, 1977; Carberry and Meng, 1986; Newell et al., 1989; Aparicio et al., 1991; Woch and Landin, 1992; Zhou et al., 2000]. Although some of the studies examined the IMF B_x effects, most of these studies were devoted to the IMF B_y effects. As a result, the relationships between the cusp and IMF B_y are better known than those between the cusp and IMF B_x. For example, although the cusp local time dependence on IMF B_y has been well established [e.g., Newell et al., 1989; Zhou et al., 2000], the relationships between IMF B_x and the cusp latitudinal locations and latitudinal widths have not yet been explicitly and quantitatively established.

We have previously developed an open-field line particle precipitation model [Wing et al., 1996; Newell and Wing, 1998]. This model, which is described in the next section, has as inputs solar wind parameters and as outputs particle precipitation and their phase space densities along a given trajectory in the ionosphere. Comparisons with Defense Meteorological Satellite Program (DMSP) data show that our model can successfully reproduce most of the large-scale features observed in the four particle precipitation regions when IMF B_x is strongly southward, as described in our previous papers [Wing et al., 1996; Newell and Wing, 1998]. The model assumed a dawn-dusk electric field that essentially reduced the convection \( \mathbf{v} = -\mathbf{E} \times \mathbf{B} \) to the two-dimensional antisunward direction. This assumption, which evidently works well near noon meridian when the IMF is predominantly southward, breaks down under different IMF orientations, as expected. For the present study, the model has been significantly improved with the inclusion of a much more realistic electric field derived from the Johns Hopkins University Applied Physics Laboratory (APL) convection model [Rauhoniemi and Greenwald, 1996]. With a more realistic electric field, the model can simulate open-field line particle precipitation for various IMF orientations. This study compares model predictions with the DMSP observations for three IMF cases: (1) the IMF is strongly southward, (2) the IMF is weakly southward, and (3) the IMF is weakly southward and strongly duskward. We investigate the locations where the cusp particles enter the magnetosphere and the dependence of the cusp morphology on IMF B_y. In particular, we study the double cusp as a particle precipitation phenomenon for IMF B_y.

Section 2 describes the open-field line particle precipitation model. Section 3 discusses model-data comparisons for the three IMF orientations mentioned above and the model prediction of the double cusp. Section 4 compares the prediction with DMSP observations in a large case study. The IMF B_y control of the cusp equatorward boundary and latitudinal width is presented in section 5. Finally, section 6 provides the summary and conclusion.

2. Open-Field Line Particle Precipitation Model

Efforts to produce a model that can withstand detailed comparison with low-altitude or midaltitude cusp data advanced significantly with the work of Onsager et al. [1993]. Instead of developing a global model self-consistently for the entire magnetosheath-magnetosphere-ionosphere system, Onsager et al. used an integrative approach that combines empirical models for different regions. We will first describe Onsager’s original model and then describe how it has been improved.

For a given southward IMF orientation, solar wind temperature and density, ionospheric convection speed, and dipole tilt angle, the model computes the phase space density of the precipitating ions and electrons in three steps. In the first step, which assumes that the magnetic moment is conserved, the ionospheric particles are traced back along the guiding centers to the magnetopause entry point by using the Stern [1985] magnetic field model modified by uniform IMF penetration [cf. Cowley et al., 1991; Wing et al., 1995; Wing and Sibeck, 1997] and a simple dusk–dawn electric field (directed toward geocentric solar magnetospheric (GSM) system positive y). The second step is to compute the acceleration \((\mathbf{j} \cdot \mathbf{E} > 0)\) or deceleration \((\mathbf{j} \cdot \mathbf{E} < 0)\) imparted on the particles when they cross the magnetopause current layers from the magnetosheath to the magnetosphere. This computation is done with the aid of the de Hoffman–Teller reference frame in which \(\mathbf{E} = 0\) [e.g., Hill and Reiff, 1977; Cowley and Owen, 1989]. From this calculation, the model obtains the velocity that the particle originally has in the magnetosheath. Finally, it computes the phase space density of particles with that velocity by using the gasdynamics calculations of Spreiter and Stahara [1985] with the assumption that all the particles, ions and electrons, have Maxwellian distributions. Assuming conservation of phase space density along particle trajectories, the model can be used to compute the differential energy flux at the location where the particle was “detected” in the ionosphere. The original model result and DMSP data comparison show that the cusp ion can be modeled fairly well but the model electron has a much more latitudinally extended entry and a much higher temperature in the mantle and polar rain regions [Onsager et al., 1993; Wing et al., 1996].

Electrons have thermal speeds far exceeding the magnetosheath flow speed and therefore can enter the magnetosphere along open field lines across the polar cap. In contrast, ions have slower thermal speeds and therefore can only enter the magnetosphere from the regions in the magnetopause where the magnetosheath flow is subsonic [Reiff et al., 1977]. Several researchers have noted that there has to be a mechanism that limits the entry of the electrons to balance the charge carried by the ions, maintaining charge quasi-neutrality in the precipitating particle populations [e.g., Reiff et al., 1977; Burch, 1985]. Solar wind electrons have been observed to have thermal and suprathermal components [e.g., Feldman et al., 1975, 1978; Fairfield and Scudder, 1985]. The original Onsager model mantle ions have much lower flux than that in the DMSP data, but ions in solar wind and magnetosphere have been observed to have \(k\) distributions. A \(k\) distribution resembles a Maxwellian at low energies but approaches a power law distri-
bution at high energies [e.g., Feldman et al., 1974; Christon et al., 1989]. For a given characteristic energy, a \( \kappa \) distribution produces a higher total flux in the ionosphere, owing to its high-energy tail. Magnetic field models have been steadily improved in recent years, e.g., with the inclusion of Birkeland currents, etc. [e.g., Tsyganenko and Stern, 1996]. Motivated by the results of these research works, we extended the original Onsager model as follows [Wing et al., 1996; Newell and Wing, 1998]: (1) imposed charge quasi-neutrality with a self-adjusting parallel electric field, (2) included suprathermal electrons, (3) used a \( \kappa \) distribution for ions, (4) replaced the Stern [1985] magnetic field model with the T96 model [Tsyganenko and Stern, 1996], and (5) used a higher and more realistic ionspheric convection velocity instead of 100 m s\(^{-1}\) which was a consequence of using the Stern [1985] magnetic field model. The details of these improvements and their significance to particle precipitation have been described in our previous works [Wing et al., 1996; Newell and Wing, 1998]. As a result, we have been able to model not just the cusp, but the entire particle precipitation region in the open-field line region for ions as well as electrons.

An example of the result of the model that incorporates all of the above processes is shown in Plate 1a (from Plate 2 of Newell and Wing [1998]). The input parameters to the model are as follows: IMF \( (B_1, B_2, B_3) = (0, -3.5, -3.5) \) nT; solar wind thermal \( n = 10 \) cm\(^{-3}\), \( T_e = 1 \times 10^5 \) K; \( T_i = 3 \times 10^4 \) K; suprathermal (halo) electron \( n_e = 0.25 \) cm\(^{-3}\), \( T_e = 1 \times 10^6 \) K; \( n_i \sim 0.3 \) cm\(^{-3}\); the ionspheric convection speed \( v = 500 \) m s\(^{-1}\); \( \kappa = 5 \); dipole tilt is 0°; and the altitude of “detected” particles is 1.13 \( R_E \), which corresponds to DMSP spacecraft altitude. The magnetic coordinates used throughout this study are the altitude-adjusted corrected geomagnetic (AAGCM) coordinates [Baker and Wing, 1989]. The solar wind thermal electron temperature is taken to be somewhat lower than that of the ions to compensate for excessive heating in the model magnetosheath. This is because the Spreiter and Stahara [1985] model is a single fluid model, which overestimates the amount of electron heating in the magnetosheath. Since the ions carry most of the kinetic energy, upon encountering the magnetopause they are thermalized to a higher temperature than are electrons. Many large-scale features that are seen in the model can also be seen in a typical DMSP pass when the IMF has a large southward component such as the one shown in Plate 1b. Not all of the features in Plate 1a, however, match precisely those in Plate 1b, because the model still has a number of shortcomings. For example, the model electric field was simply a dawn–dusk electric field applied uniformly throughout the entire magnetosphere. Nonetheless, the model is a significant improvement over the original model, as can be seen, for example, from comparison of Plate 1a in this paper and Plate 1 of Wing et al. [1996].

The success of the open-field line particle precipitation model strongly suggests that the same large-scale processes govern all four particle precipitation regions in the open-field line domain, namely, open-field line LLBL, cusp, mantle, and polar rain [Wing et al., 1996]. Open-field line LLBL is the region closest to the open/closed boundary. When the field line first becomes open, electrons having a higher speed than ions flow into the magnetosphere ahead of ions. Charge quasi-neutrality and the resulting parallel electric field, however, limit the number of electrons that can enter. Thus in this region, few electrons and ions are present. In the cusp, the ions have reached the ionsphere, and intense fluxes of ions and electrons are usually observed. In this region, the electrons and ions can enter the magnetosphere relatively freely because the numbers of magnetosheath ions and electrons are already balanced, resulting in little or no parallel electric field. In the mantle region, fewer ions can enter as the magnetosheath flow becomes increasingly tailward and larger, whereas the magnetospheric magnetic field and hence precipitating particle velocity becomes more sunward, a condition which is less favorable for particle entries. In this region, \( J \cdot E < 0 \), which means that the magnetic stress at the magnetopause is directed to decelerate the plasma [e.g., Hill and Reiff, 1977; Cowley and Owen, 1989]. Some of the solar wind thermal or core electron entries are limited by the ensuing parallel electric field that arises to maintain charge quasi-neutrality. Finally, in the polar rain region, no significant amount of ions enter the magnetosphere, and the parallel electric field rises to the level where only the higher-energy tail end of the core electrons and the suprathermal electrons, having higher energy, can enter the magnetosphere.

The above example illustrates that despite having only the simple duskward electric field, the model can simulate particle precipitation for the classical southward IMF case fairly well, producing large-scale features that are found in the data. The reason is that near the noon meridian the magnetic field line convection is typically antisunward, which results in an electric field that is nearly duskward [e.g., Heelis, 1984; Heppner and Maynard, 1987; Weinmer, 1995; Ruohoniemi and Greenwald, 1996]. However, when the IMF has a significant \( y \) component, the field line convection acquires a significant east–west component that makes the dawn–dusk electric field in the model grossly inaccurate.

In order to obtain a more accurate electric field, the statistical APL convection patterns are incorporated into the model [Ruohoniemi and Greenwald, 1996]. The APL convection patterns, which give the electric potential in the ionosphere, were produced statistically from 6 years of Goose Bay HF radar observations for eight intervals of clock angle and three steps in magnitude in the \( y-z \) plane. The potential was produced at 1° latitudinal and 2° longitudinal resolution from 56° \( \Lambda \) to 89° \( \Lambda \) at an ionospheric altitude of 300 km. For the purpose of computing electric field, a three-dimensional grid of 0.2 \( \times \) 0.2 \( R_E \) was produced in the dayside magnetosphere and ionosphere. The potential value at each point in the grid was obtained by mapping along the T96 field line to the ionosphere where four-point linear interpolation is performed from the APL convection pattern. The electric field anywhere in the magnetosphere and ionosphere could then be derived simply from \( E = -\nabla \phi \), where \( \phi \) is potential from the grid. In deriving the electric field, no potential drop along the field line is assumed, and the effects of corotation and polarization due to charge separation are ignored. Maynard et al. [1995] calculated the effects of corotation on the Heppner and Maynard [1987] convection patterns and found that the effects are small at high latitudes. Similarly, the polarization charges resulting from the different drift paths of ring current ions and electrons have significant effects only in the inner magnetosphere [Maynard et al., 1995; Harel et al., 1981]. In the APL pattern, the zero potential boundary is set somewhat arbitrarily at 55° \( \Lambda \) to 60° \( \Lambda \) depending on the magnitude and orientation of the IMF. Fortunately, this has little consequence to the open-field line region that usually resides poleward of 70° \( \Lambda \).

Although the APL convection pattern provides a more accu-
rate electric field, it is not self-consistent with the T96 magnetic field model. The T96 model itself has its own deficiencies; e.g., it does not take into account the effects of the IMF on the magnetopause shape and size, which in turn can affect the cusp footprint [e.g., Shue et al., 1997]. The Spreiter and Stahara [1985] magnetosheath model is a single-fluid gasdynamic model that does not take into account the magnetic field. In addition, the model has not taken all the particle precipitation processes into account such as the wave–particle interaction, nonadiabatic motions, particle diffusion across the magnetopause, etc.

3. Model-Data Comparisons

DMSP are Sun-synchronous satellites in nearly circular polar orbit at an altitude of roughly 835 km and a period of approximately 101 min per orbit. The SSJ4 instrumental package included on all recent DMSP flights uses curved plate electrostatic analyzers to measure ions and electrons from 32 eV to 30 keV in 19 logarithmically spaced steps [Hardy et al., 1984]. One complete 19-point electron and ion spectrum is obtained each second, during which time the satellite moves 7.5 km. The satellites are three-axis stabilized, and the detector apertures always point toward local zenith. This means that at the latitudes of interest herein, only highly field-aligned particles well within the atmospheric loss cone are observed. The data are available at the Johns Hopkins University Applied Physics Laboratory and are publicly accessible through a web site at http://sd-www.jhuapl.edu/Aurora.

Using the model and DMSP SSJ4 data, this study investigates the cusp characteristics for three IMF cases: (1) the IMF is strongly southward, (2) the IMF is weakly southward, and (3) the IMF is weakly southward and strongly duskward. The first two cases demonstrate how the realistic electric field improves the model as compared with our previous results [Newell and Wing, 1998] and how the model results compared with the previous observational studies. The third case hopefully leads to new insights, as surprisingly fewer studies have looked at the cusp properties in detail when the y component dominates the IMF.

In order to facilitate comparisons of the model cusp morphology for the three IMF orientations, the input parameters are kept the same in all three cases, except of course for the IMF. Even the IMF inputs are not changed drastically from one case to another. For example, the input solar wind and IMF for the first case (section 3.1) and the third case (section 3.3) are the same, except that the IMF has been rotated $-90^\circ$ in the y–z plane. Thus the solar wind input parameters for the model calculations and those for the DMSP passes presented in this paper in general are not exactly the same. Because of this and the model limitations, some of which were mentioned above, the model results are not expected to match the DMSP observations exactly in every detail. Hence we could only compare the large-scale morphologies and features in the model results with the DMSP observations.

3.1. First Case: Strongly Southward IMF

The previous version of the model could produce the classic southward IMF cusp that looks fairly realistic near the noon meridian, even with a simple dawn–dusk electric field, for the reason described above. For example, the large-scale features in Plates 1a and 1b are very similar. However, detailed comparisons of the IMF energy-latitudinal dispersions, which is highly dependent on $E \times B$, reveals some differences. In the previous model, the input IMF, the magnetospheric $E$, and the convection $v$ are independent of each other and not necessarily consistent with each other. As a result, the model does not produce cusp and mantle dispersions that resemble closely those in the data. However, in the present newly improved model, the input IMF determines the APL convection pattern and hence $E$ and $v$. Therefore $E$ and $v$ are more self-consistent with the IMF, resulting in improved ion dispersions.

As an example, we reexamine the same DMSP pass on December 24, 1983, which was used in our previous model-data comparison. This is displayed in Plate 2b, which differs from Plate 1b in that it zooms in on the cusp and mantle regions, focusing more on the energy-latitudinal dispersion. The input parameters are IMF $(B_x, B_y, B_z) = (-3.4 \ nT, -0.5 \ nT, -12.3 \ nT)$, solar wind thermal $n = 11 \ cm^{-3}$, $T_i = 1 \times 10^5 \ K$, $T_e = 3 \times 10^4 \ K$, and suprathermal (halo) electron $n_e = 0.2 \ cm^{-3}$, $T_e = 1 \times 10^6 \ K$, dipole tilt of $3^\circ$, $\kappa = 7$, and the model "trajectory" is nearly along the noon meridian at an altitude of 1.13 $R_E$. The model result is shown in Plate 2a. Comparisons of Plates 1 and 2 show that the most significant improvement is that the cusp and mantle dispersions more closely resemble the observations. The model cusp equatorward boundary is located at $71^\circ$, which is very close to the statistical cusp boundary for the same IMF condition in this study (section 5) as well as in the previous studies [e.g., Carbery and Meng, 1986; Newell et al., 1989; Zhou et al., 2000].

Figure 1a shows the locations of the z coordinates of the entry points of the ions in Plate 2a. With a small IMF $B_y$, the particle trajectory basically follows a path along the noon meridian ($\gamma \sim 0 \ R_E$). Within each field line, the lower-energy particle comes from a lower latitude. The model cusp ions originate from the low-latitude magnetopause, within $7 \ R_E$ from the subsolar point. This result is in agreement with the previous observational cusp studies during periods of southward IMF [e.g., Reiff et al., 1977; Lockwood and Smith, 1992]. In this study, low-latitude magnetopause refers to the magnetopause locations where $|z| < 5 \ R_E$, midlatitude refers to the region $5 \ R_E < |z| < 10 \ R_E$, and high latitude refers to regions with $|z| > 10 \ R_E$.

3.2. Second Case: Weakly Southward IMF

The IMF morphology during periods of weakly southward IMF is investigated next. To facilitate comparison with the first case, the input parameters to the model remain the same as before except for the IMF, which has been changed to IMF $(B_x, B_y, B_z) = (-0.5, -0.5, -3) \ nT$. The model output and a DMSP pass under similar IMF conditions are shown in Plate 3. Plate 3 shows that the energy-latitudinal dispersion in the model result resembles closely that in the observation. As in the southward IMF case, the location of the cusp equatorward boundary at 76.5$^\circ$ A is very close to the statistical cusp boundary for similar IMF [e.g., section 5] [Carbery and Meng, 1986; Newell et al., 1989; Zhou et al., 2000].

One of the main differences between this and the previous IMF case is that the cusp location moves to higher latitude as IMF $B_z$ increases, a well-documented phenomenon in many observational studies [e.g., Carbery and Meng, 1986; Newell et al., 1989; Zhou et al., 2000]. The movement of the cusp location has been interpreted in terms of merging and the flux erosion on the dayside when IMF $B_z$ turns more southward [e.g.,
Plate 1. (a) Result of the model calculations with a simple dawn-dusk electric field and (b) a DMSP observation during periods of strongly southward IMF. The spectrogram shows log differential energy flux, in units of eV/cm² s sr eV, from 32 eV to 30 keV, with the ion energy scale inverted. The lower of the two line plots shows the average energy in eV for the electrons (black) and ions (orange), and the top line plot is of integral energy flux in units of eV/cm² s sr.
Plate 2. (a) Results of the model calculations with a realistic electric field for a strongly southward IMF case and (b) a DMSP observation under similar IMF conditions. See caption of Plate 1 for the descriptions of units, scales, etc.
Plate 3. Same as Plate 2, except for a weakly southward IMF case. See caption of Plate 1 for descriptions of units, scales, etc.
Plate 4. Same as Plate 3a, except for a strongly duskward and weakly southward IMF case. The calculation result shows two cusp regions that are latitudinally separated (double cusp). The model stops tracing at $x < -50 R_E$, which explains the sudden cutoff of the polar rain electron spectra. See caption of Plate 1 for descriptions of units, scales, etc.
3.3. Third Case: Weakly Southward and Strongly Duskward IMF

The previous two cases demonstrate that as a result of using the electric field from the APL convection patterns, the open-field line particle precipitation model is able to obtain more realistic energy-latitude dispersions under southward IMF $B_z$ conditions. However, the main benefit of incorporating APL convection patterns is that the model can now be used to investigate the effects of nonsouthward IMF orientation. For this study, we examine the case when the IMF $z$ component is weakly negative and the $y$ component is strongly positive. The input parameters are the same as before, except that now the IMF $(B_y, B_z) = (-3.4, 12.3, -0.5)$ nT. This IMF configuration amounts to $-90^\circ$ rotation in the $y-z$ plane from the strongly southward IMF case in section 3.1, while maintaining the same magnitude.

When the IMF does not have the classical southward orientation, the evolution of the magnetosheath and magnetospheric
magnetic field orientation after merging is important. This is because as the open-field line convects, the relative orientation between the IMF/magnetsosheath field line and magnetospheric field line changes, which in turn alters the particle acceleration/deceleration as it crosses the magnetopause [e.g., Cowley and Owen, 1989]. It is, therefore, constructive to examine closely the evolution of the field line orientation right after merging. We consider the Northern Hemisphere for IMF $B_z > 0$. The discussion can be applied to the Southern Hemisphere and/or IMF $B_z < 0$ case as well with the usual consideration of antisymmetries. According to the antiparallel merging model and observations, when IMF has a large $y$ component and a small $z$ component, merging occurs at postnoon at the high-latitude magnetopause in the Northern Hemisphere [e.g., Crooker, 1979; Gosling et al., 1991; Newell et al., 1995]. Because the magnetosheath and magnetospheric field lines are of different orientation, there is a discontinuity or a kink where the two field lines are joined in the magnetopause. A curvature force or field line tension arises and acts to straighten the connected field line. Immediately after merging, the field line tension pulls the open field line westward toward prenoon as the field line straightens out. Initially, the westward motion of the field line is stronger than the poleward motion caused by the antisunward flow of the magnetosheath field line. Hence the overall motion of the field line is mainly westward. However, at prenoon, the connected field line becomes less kinked, and as a result the $B_z$ dependent westward motion gets weaker and the field line drifts mostly poleward toward the nightside [e.g., Smith and Lockwood, 1996]. As it does, the magnetosheath line acquires $-z$ and $+x$ components (see, for example, Figure 5 of Crooker et al. [1998]). The model here does not include explicitly this evolution of the merged field line, but this effect is approximated in a rather ad hoc fashion by increasing the magnitude of merged magnetosheath $B_z$ by a factor of 10 and reducing the $B_y$ and $B_x$ by a factor of 5 at high-latitude prenoon. The merged field line evolution effect is less important for the classical southward IMF cases near noon. This is because the field line tension and motion is only in the north–south direction, leaving the relative orientation of the magnetosheath field line with respect to the magnetospheric field line approximately unchanged [Cowley et al., 1983].

The model result, shown in Plate 4, has two rather unusual features that are not usually seen in the classical southward IMF cusp: (1) two regions of cusp precipitation that are latitudinally separated (double cusp) and (2) the cusp energy-latitude dispersion. The model stops tracing whenever the particle reaches $x < -50 R_E$. This explains the sudden cutoff of the polar rain electrons in Plate 4. However, the polar rain in this re-

![APL convection model](image)

**Figure 2.** Locations of the lower- and higher-latitude cusp of the double cusp superimposed on the APL convection pattern for a strongly duskward IMF case. In the lower-latitude cusp (L) region, the $E \times B$ drift is weakly dawnward, whereas in the higher-latitude cusp (H) region, it is strongly dawnward and poleward. The poleward drift gets stronger with increasing latitude.
The GSM (a) x, (b) y, and (c) z coordinates of the ion magnetopause entry points for model cusp ions in Plate 4. Equatorward and poleward boundaries of the two cusps in the double cusp are marked with dashed lines in Figure 3c.

Figure 3. The GSM (a) x, (b) y, and (c) z coordinates of the ion magnetopause entry points for model cusp ions in Plate 4. Equatorward and poleward boundaries of the two cusps in the double cusp are marked with dashed lines in Figure 3c.

The locations of these two cusps and the model trajectory relative to the convection patterns are shown in Figure 2. The lower- and higher-latitude cusps are labeled L and H, respectively. In the region where the lower-latitude cusp is located, \( \mathbf{v} = \mathbf{E} \times \mathbf{B} \) is mostly dawnward, and in the equatorward edge of the cusp, \( \mathbf{v} \) has a small equatorward (sunward) component. However, as can be deduced from the contours in Figure 2, the magnitudes of \( \mathbf{E} \) and \( \mathbf{v} \) are small in this region. On the other hand, in the region of the higher-latitude cusp, \( \mathbf{v} \) and \( \mathbf{E} \) have larger magnitudes, and \( \mathbf{E} \times \mathbf{B} \) convection is dawnward and poleward (antisunward). As a result, the lower-latitude cusp ions experience weak \( \mathbf{E} \times \mathbf{B} \) dawnward drift during their flights from the magnetopause to the ionosphere, whereas the higher-latitude cusp ions experience stronger \( \mathbf{E} \times \mathbf{B} \) dawnward and poleward drift.
The lower-latitude cusp ions originate at low latitude in the magnetosheath, \( z = -5 \) to \(+5 R_E \), whereas the higher-latitude cusp ions originate mostly from the high-latitude magnetosheath, \( z = 7 \) to \(13 R_E \). This is shown in Figure 3, which plots the locations of the entry points of the cusp ions. Furthermore, Figure 3b shows that near noon, lower-latitude cusp ions originate from the prenoon magnetosheath, \( y < 0 \). In the T96 model, the input IMF \( B_y \) and \( B_z \) affect the magnetospheric magnetic field line such that the magnetospheric \( B_y \) and \( B_z \) increase/decrease by an amount that is roughly proportional to IMF \( B_y \) and \( B_z \), respectively. This “IMF penetration” in the model is rather realistic and has an observational basis [e.g., Cowley and Hughes, 1983; Hughes and Cowley, 1986; Nagai, 1987; Wing et al., 1995; Wing and Sibeck, 1997]. Thus when the IMF has strong duskward (+y) component, the magnetospheric magnetic field line gains a significant +y component. As a result, in the presence of small \( E \times B \) drift, the lower-latitude cusp ions of all energies originate from the prenoon \( (y = -4 \) to \(-2 R_E) \) magnetosheath. On the other hand, the higher-latitude cusp ions experience strong downward \( E \times B \) drift before precipitating down in the ionosphere. This means that the lower-energy cusp ions enter the magnetosphere at noon or postnoon \( (y > 0) \) and then \( E \times B \) drift downward to prenoon before precipitating near noon, whereas the higher-energy cusp ions enter the magnetosphere at prenoon before precipitating near noon.

In the classical southward IMF case, the near-noon magnetospheric magnetic field line and the \( E \times B \) convection have little \( y \) component. Consequently the precipitating cusp ions at noon originate approximately from the noon magnetosheath. Once they enter the magnetosphere, they undergo strong \( E \times B \) poleward drift, resulting in the classical cusp dispersion in which the ion characteristic energy decreases with increasing latitude, as shown in Plates 2 and 3.

In contrast, when the IMF has a strong duskward component, the cusp dynamics are more complex, producing the double cusp that appears in Plate 4. The noon precipitating cusp ions no longer originate from the noon magnetosheath. The lower-latitude cusp ions near noon originate at low-latitude prenoon. Once they cross the magnetopause, they undergo \( E \times B \) downward drift, albeit only moderately, during their flight from the magnetosphere to the ionosphere. The resulting cusp exhibits less energy-latitude dispersion than that in the classical southward IMF case. The dispersion is in the azimuthal direction that cannot be easily detected in the fixed meridian satellite orbit. This cusp which is dispersionless, i.e., the characteristic energy does not change much with latitude, perhaps falls into the category of stagnant or weak IMF \( B_z \) cusp in the classification scheme developed by Yamauchi and Lundin [1994] or can be associated with “confused” signatures observed during weak IMF \( B_z \) in the work of Reiff et al. [1980].

The higher-latitude cusp ions entry points range from prenoon \((y = -5 R_E)\) to slightly postnoon \((y = 2 R_E)\) magnetopause, as depicted in Figure 3. Because of the strong \( E \times B \) downward drift, the lower-energy ions enter from locations duskward of the entry points for higher-energy ions. Once the ions are in the magnetosphere, they undergo \( E \times B \) poleward and downward drift. Because of a significant poleward component of the \( E \times B \) drift, the dispersion of the higher-latitude cusp has some resemblance to that of the classic southward IMF cusp.

The mantle ions, having lower energies, have a greater proportion that originates in the postnoon magnetosheath, as indicated in Figure 3. The trajectory of the model spacecraft moves away toward prenoon as it travels northward. This explains why the higher-energy mantle ions come from entry points that are dawnward of those in the cusp. As can be seen in Figure 2, the \( v = E \times B \) convection in the mantle region is increasingly predominantly poleward, which results in mantle dispersion that is similar to that of the classical southward IMF mantle.

The observational confirmation of the model prediction of a double cusp is presented next.

4. Double Cusp: Observational Confirmation

The previous section presents a model calculation predicting a near-noon double cusp (two cusp regions that are separated latitudinally) in the Northern Hemisphere when the IMF is strongly duskward and weakly southward. Taking into consideration the usual prenoon/postnoon and hemispherical antisymmetries, the same process outlined above would also produce a double cusp during periods of strongly dawnward IMF and/or in the Southern Hemisphere. Four examples of near-noon DMSP passages during periods of large \( |IMF B_y| \) are presented in Plate 5. The first two examples, Plates 5a and 5b, are from periods when the IMF was strongly dawnward, and the last two, Plates 5c and 5d, are from the periods when the IMF was strongly duskward. Figure 4 shows that the IMF is relatively stable prior, during, and after these events. The IMF was obtained from the IMF 815-s database provided by the NASA National Space Science Data Center (NSSDC) web site. The two vertical dashed lines in Figure 4 mark the start and end times of the double-cusp events, shifted by \( \Delta t \), the solar wind propagation delay from IMF 8 to the ionosphere. Here \( \Delta t \) is estimated rather crudely as \( \Delta t \) = ballistic propagation of solar wind to the magnetopause standoff distance \((x = 10 R_E) + 5 \) min propagation in the magnetosheath [e.g., Lockwood et al., 1989; Ridley et al., 1998] + 3.5 min for 1-keV ions to travel along the field line from the magnetopause to the ionosphere \((15 R_E) \) [e.g., Carlson and Torbert, 1980]. It is well known that cusp properties frequently show great variability even for roughly the same IMF conditions, as there are other parameters that influence the cusp properties, e.g., local time effects, wave–particle interaction, solar wind dynamic pressure, dipole tilt angle, etc. For example, Yamauchi and Lundin [1994] sort the cusp events by IMF \( B_z \) and found that several types of cusp variations exist even within each IMF category. However, as discussed below, all four examples in Plate 5 exhibit common features that are found in the model result shown in Plate 4.

Plate 5a shows that there are two cusps: one at lower latitude and one at higher latitude. The separation between the two cusps is narrower than the model result shown in Plate 4. Nonetheless, it is clear that there are two separate distinct cusps, as can be seen from the ion differential energy flux \( (dI/dE) \) level as well as dispersion. The lower-latitude cusp exhibits higher \( dI/dE \) with almost no dispersion, except at the poleward edge. In contrast, the higher-latitude cusp exhibits lower \( dI/dE \) with the classical dispersion. The separation between the two cusps can sometimes be even narrower to give the impression of just one cusp with an extended latitudinal width such as the one shown in Plate 5b. This particular cusp is perhaps similar to the hybrid cusp example of Woch and Lundin [1992]. Their hybrid cusp shows a cusp with a rather extended latitudinal width, and the convection is essentially dawnward with a small sunward component at the equatorward
Plate 5. DMSP double cusp events (a, b) during periods of strongly dawnward IMF and (c, d) during periods of strongly duskward IMF. In Plate 5b the separation between the lower-latitude and the higher-latitude cusp narrows so that the two appear to form one cusp with extended latitudinal width. See caption of Plate 1 for descriptions of units, scales, etc.
Plate 5. (continued)
Figure 4. IMP 8 15-s IMF for the double-cusp events shown in (a) Plate 5a, (b) Plate 5b, (c) Plate 5c, and (d) Plate 5d. The two vertical dashed lines mark the start and end times of the double-cusp events, shifted by the solar wind propagation delay from IMP 8 to the ionosphere.
Mar 8 1990  IMP 8 located at ~ (21, 25, -2) R_E

(c)

Universal Time

Jul 22 1992  IMP 8 located at ~ (27, 3, 15) R_E

(d)

Universal Time

Figure 4. (continued)
edge of the cusp. Plate 5c clearly shows a double cusp with a clear separation between the two cusps. The lower-latitude cusp exhibits lower $d_j/dE$ than the higher-latitude cusp. Again, the lower-latitude cusp exhibits an absence of dispersion, whereas the higher-latitude cusp has the usual dispersion. This example shows that a double cusp can also occur when IMF $B_z$ is slightly positive and $|\text{IMF } B_z|$ is large, as shown in Figure 4c. IMF $B_z$ averaged $-1$ nT for the duration of the cusp encounter, but it briefly dipped below $0$ nT and averaged $-1$ nT a few minutes before the cusp encounter. Our experience with the APL convection patterns indicates that this type of IMF $B_z$ fluctuation does not cause much, if any, observable change in the convection pattern, implying little or no significant change in the magnetospheric and ionospheric $E$, $v$, etc. The IMF and the convection pattern were essentially dominated by IMF $B_z$, which averaged $-9$ nT during the encounter. Finally, Plate 5d shows yet another double cusp. There is a narrow but clear separation between the two cusps. Again, the two cusps have two distinct ion dispersions that are similar to the two corresponding cusps in Plate 4. The two cusps can also be distinguished from their $d_j/dE$ level.

Above we presented four case examples of a double cusp. A larger survey is now considered.

The DMSL database for the period of 1985–1995 was searched for cusp events when the IMF had a large $y$ component and a small negative $z$ component. The automated algorithm that identifies auroral oval boundaries and structures based on DMSL particle precipitation data developed by Newell et al. [1991a, 1991b] was used to search for these events. IMF was obtained from the IMP 8 15-s database provided by the NASA NSSDC web site. The database was divided into two classes: IMF $B_{z}<0$ (toward sector) and IMF $B_{y}>0$ (away sector).

The criteria for selecting IMF $B_{y}>0$ events are (1) IMF $-4$ nT $\leq B_{y} \leq 0$ nT and $B_{z} \geq 8$ nT and (2) the IMF has been relatively stable so that criterion 1 is satisfied for at least 15 min. The latter requirement attempts to restrict events to those in a quasi-steady state. The search returns a total of 22 cusp events. These 22 events, 16 events, or 73% of the total events, show double cusps or latitudinally extended cusps, while six events do not.

The criteria for selecting IMF $B_{z}<0$ are the same as above except that the IMF $B_y$ condition is reversed: (1) IMF $-4$ nT $\leq B_{y} \leq 0$ nT and $B_{z} \leq -8$ nT, and (2) the IMF has been relatively stable so that criterion 1 is satisfied for at least 15 min. There are 18 cusp events that satisfy the IMF criteria. Of these 18 events, 14 events show double cusps or latitudinally extended cusps and four do not. This amounts to 77% of the total events with double cusps or latitudinally extended cusps.

In all, it appears that double cusps or latitudinally extended cusps appear fairly frequently, approximately 75% of the time, when IMF has a large (positive or negative) $y$ component and a small negative $z$ component.

5. IMF $B_y$ Control of Cusp Location and Latitudinal Width

There have been many statistical studies of the IMF and solar wind control of the cusp properties, e.g., locations, boundaries, etc. [e.g., Carberry and Meng, 1986; Newell et al., 1989; Aparicio et al., 1991; Zhou et al., 2000]. However, none of these studies has examined the IMF $B_y$ control of the latitudinal cusp width or the cusp equatorward boundary. The model calculations and the case study above suggest that the IMF $B_y$ should have some influence on the two cusp properties. For example, the cusp equatorward boundary for weakly southward and weakly downward IMF in Plate 3a is located at higher latitude than that for strongly downward IMF in Plate 4. Also, the cusp latitudinal width increases for the type of double cusp events shown in Plate 3b, e.g., when the latitudinal separation between the two cusps is very narrow. With years of DMSL data available, these two cusp properties can now be determined statistically.

For selecting the cusp events, we used the same DMSL automated cusp identification algorithm in the case study above to search cusp events in the DMSL data for the period of one solar cycle, 1985–1995 [Newell et al., 1991a, 1991b]. Upon inspection of several double cusp events, it is found that this automated algorithm works reasonably well most of the time. However, it sometimes identifies cusps with low-energy flux as LLBL. Although this inevitably introduces noise into the cusp equatorward boundary and latitudinal width computation, there has been no perfect automated cusp identification algorithm. NASA NSSDC provides the IMF 8 simultaneous hourly averaged solar wind and IMF data. With this method and database, there are a total of 2259 cusp events identified. The cusp equatorward boundary and latitudinal width are correlated with the IMF $B_{y}$ and $B_{z}$. In each case, the data are divided according to the sign of the IMF component. Thus there are four cases to be considered.

5.1. Cusp Equatorward Boundary

It is well established that the cusp latitudinal location correlates well with the IMF $B_y$. The same result holds with our data and methodology, which uses a computer algorithm to search the DMSL data for cusp events for the period of one solar cycle. The result can be seen in Figure 5a, which includes 2177 data points. The results of the linear least squares fits are as follows: cusp equatorward boundary (ceb) = $0.78 \pm 0.03$ IMF $B_{y} + 77.3 \pm 0.1^o$ Λ and ceb = $6 \times 10^{-4} \pm 0.04$ IMF $B_{y} + 77.9 \pm 0.1^o$ Λ for the southward and northward IMF, respectively. The correlation coefficients are 0.55 and $5 \times 10^{-4}$ for southward and northward IMF, respectively. The near-zero correlation coefficient of the latter simply reflects the nearly constant locations of the cusp equatorward boundary latitude during periods of northward IMF, as can also be seen in the scatter plot in Figure 5a. These results are in very good agreement with the previous result of ceb = $0.76$ IMF $B_{y} + 77.0^o$ Λ and ceb = $0.11$ IMF $B_{y} + 77.2^o$ Λ [Newell et al., 1989] and are comparable to ceb = $0.86$ IMF $B_{y} + 79.5^o$ Λ and ceb = $0.07$ IMF $B_{y} + 79.2^o$ Λ for southward and northward IMF, respectively [Zhou et al., 2000]. The latter results were obtained with mid-altitude Polar satellite observations, which may explain the slight location shift. The decrease of the cusp latitude with decreasing IMF $B_y$ during periods of southward IMF $B_y$ has been interpreted as the effect of merging and flux erosion on the dayside [e.g., Aubry et al., 1970; Zhou et al., 2000]. In contrast, IMF $B_y$ does not control much of the cusp equatorward boundary during periods of northward IMF, as shown in Figure 5a.

The above relationship between IMF $B_y$ and the cusp equatorward boundary is obtained when all cusp events are included. If the cusp events with large $|\text{IMF } B_y|$ are removed
from the data, then the cusp equatorward boundary moves to higher latitude. There are 798 such cusp events which were chosen with the IMF $B_z$ criterion: $-3 \text{ nT} \leq \text{ IMF } B_z \leq 3 \text{ nT}$. The results of the linear least squares fits are $0.81 \pm 0.05 \text{ IMF } B_z + 77.7^\circ \pm 0.2^\circ \Lambda$ and $\text{ ceb } = 0.04 \pm 0.06 \text{ IMF } B_z + 78.1^\circ \pm 0.2^\circ \Lambda$ for southward and northward IMF, respectively; their correlation coefficients are 0.54 and 0.04, respectively. This difference is statistically significant; e.g., for IMF $B_z = 0$, the difference of the cubs $(77.7 - 77.3)$ is larger than the uncertainty $(\sqrt{0.1^2 + 0.2^2})$. The poleward shift, resulting from the removal of large $|\text{ IMF } B_z|$ events, ranges from $0.1^\circ$ to $0.4^\circ$ as IMF $B_z$ increases from $-10$ to $0$ nT. Thus the poleward shift is greater for weakly southward IMF than for strongly southward IMF. This shift is consistent with the removal of the double-cusp events. However, there could be other factors at work simultaneously as well, such as the effect of merging and flux removal as discussed next.

Merging can also occur during periods of large IMF $B_y$. Although the ensuing flux erosion is expected to move the cusp latitudinal location equatorward as in the case for southward IMF, this relationship has never been quantified. We selected 1337 cusp events with small IMF $B_z$, $-3 \text{ nT} < \text{ IMF } B_z < 3 \text{ nT}$. The results of the linear least squares fits of IMF $B_y$ versus the equatorward boundary of the cusp are shown in Figure 5b. The linear least squares fit results in $\text{ ceb } = 0.12 \pm 0.05 \text{ IMF } B_y + 77.3^\circ \pm 0.2^\circ \Lambda$ and $\text{ ceb } = 0.14 \pm 0.04 \text{ IMF } B_y + 77.7^\circ \pm 0.2^\circ \Lambda$ for negative and positive IMF $B_y$, respectively. The correlation coefficient is 0.10 and $-0.13$ for IMF $B_y < 0$ and IMF $B_y > 0$, respectively. The slopes are much smaller than those for the southward IMF case. The cusp equatorward boundary moves
Cusp Latitudinal Width

Figure 6. Cusp latitudinal width as a function of (a) IMF \( B_z \) and (b) IMF \( B_y \). The medians in 2-nT IMF \( B_z \) and IMF \( B_y \) bins are indicated by horizontal bars in Figures 6a and 6b, respectively.

The cusps slightly equatorward when IMF \( B_z \) increases in magnitude, but this effect is much weaker than the southward IMF effect. The small correlation coefficients indicate the presence of rather large scatter in the data distribution, but they are statistically significant considering the size of the data set, namely, 635 and 696 points for IMF \( B_z < 0 \) and IMF \( B_z > 0 \), respectively. A t test indicates that the probability for IMF \( B_z \) and ceb being uncorrelated is <1% [e.g., Pugh and Winslow, 1966]. Furthermore, this result is consistent with the poleward shift of ceb in Figure 5a when large \( |IMF\ B_z| \) events are removed, as discussed in the previous paragraph.

The relationships between IMF and ceb can be illustrated more easily by the plots of their medians. The median values of ceb in 2-nT IMF \( B_z \) and \( B_y \) bins are indicated by horizontal bars in Figures 5a and 5b, respectively. The correlation coefficients of these medians are 0.99, −0.57, 0.93, and −0.98 for IMF \( B_z < 0 \), IMF \( B_z > 0 \), IMF \( B_y < 0 \), and IMF \( B_y > 0 \), respectively.

The cusp equatorward boundary is clearly more affected by IMF \( B_z \) than IMF \( B_y \). The more dominant effect of IMF \( B_z \) over IMF \( B_y \) is typical for many cusp properties.

5.2. Cusp Latitudinal Width

In contrast to the cusp equatorward latitude, the effect of IMF \( B_y \) is at least as strong as that of IMF \( B_z \) on the cusp latitudinal width near the noon meridian, 1100 ≤ MLT ≤ 1300. Figure 6 shows that the cusp latitudinal width increases with \( |IMF\ B_y| \) and \( |IMF\ B_z| \). The misclassification of weak cusps as open-field LLBL partly contributes to the large scatter in the
In this study, the cusp latitudinal width is obtained within 1 to 2 min from an individual cusp observation made by a DMSP pass that reaches \(81^\circ \lambda\) or higher. This requirement helps eliminate passes that just graze the cusp; e.g., the statistical location of the cusp is well below \(81^\circ \lambda\) [e.g., Newell et al., 1989].

In Figure 6b, all the events have been selected so that they have a weakly southward IMF component, \(-3 \, nT \leq IMF_{B_z} \leq 0 \, nT\), which restricts the number of events to 396. The medians of the cusp latitudinal width (clw) in 2-nT IMF \(B_z\) bins are plotted as horizontal lines in Figure 6b. The medians are computed only for bins that contain five data points or more. The least squares fits of the medians are \(clw = -0.06 \pm 0.004 \, IMF_{B_z} + 0.5^\circ \pm 0.02^\circ \) and \(clw = 0.04 \pm 0.02 \, IMF_{B_z} + 0.5^\circ \pm 0.1^\circ\) for IMF \(B_z < 0\) and IMF \(B_z > 0\), respectively; the correlation coefficients are \(-0.99\) and 0.76, respectively. This result is consistent with our case study above which shows that at times the double cusp, associated with large \(|IMF_{B_z}|\), forms a single cusp with extended latitudinal width, e.g., Plate 5b.

Figure 6a shows the effect of IMF \(B_z\) on the cusp latitudinal width. The results of the least squares fit of the medians are \(clw = -0.03 \pm 0.01 \, IMF_{B_z} + 0.6 \pm 0.05 \) and \(clw = 0.04 \pm 0.02 \, IMF_{B_z} + 0.4 \pm 0.1\) for southward and northward IMF, respectively. Their correlation coefficients are \(-0.91\) and 0.84 for southward and northward IMF, respectively. Again, only bins containing five or more data points are included in the median calculations. Figure 6a shows a trend similar to that of Figure 5 of Zhou et al. [2000], especially if their extremely small (IMF \(B_z < -8\)) and large IMF \(B_z\) (IMF \(B_z > 5\)) bins, which contain many fewer points, are excluded from their figure. In any case, the scatter is very large in both studies.

6. Discussion and Summary

Our particle precipitation model has been significantly improved with the addition of realistic electric field observed from the DMSP convection patterns. As a result, the model can calculate the \(E \times B\) drift more accurately, resulting in a more realistic cusp and mantle ion dispersion. This is illustrated clearly in the two IMF cases: (1) strongly southward and (2) weakly southward. Two main differences between these two cases are that (1) the cusp ions enter from the low-latitude magnetopause \(|z| < 5\, R_E\) in a strongly southward IMF case, but the entry points move to higher latitude magnetopause as IMF \(B_z\) increases, and (2) in the ionosphere, the cusp location also moves poleward with increasing IMF \(B_z\) during periods of southward IMF.

The IMF \(B_z\) dependence of the entry points may partly explain the wide-ranging cusp injection points along the field line reported during periods of southward IMF in previous studies, e.g., 18 and 26 \(R_E\) away [Reiff et al., 1977], 7 to 10 \(R_E\) [Carlson and Torbert, 1980], 8 to 12 \(R_E\) [Menietti and Burch, 1988], and 10 \(R_E\) [Woch and Lundin, 1992]. The model cusp locations in these two cases are very close to the statistical cusp locations obtained in this study as well as in the previous studies [e.g., Newell et al., 1989]. The movement of the cusp location in response to the IMF \(B_z\) during periods of southward IMF has been interpreted as the effect of merging and the subsequent flux tube erosion on the dayside [e.g., Zhou et al., 2000].

When the IMF is strongly duskward and weakly southward, the model predicts the occurrence of a double cusp near the noon meridian in the Northern Hemisphere: one at higher latitude and one at lower latitude. This prediction was subsequently confirmed in the DMSP data under similar IMF conditions. Note that the discussion here pertains to Northern Hemisphere and strongly duskward IMF. However, it also applies to Southern Hemisphere and strongly dawnward IMF with the usual prenoon/postnoon and hemispherical asymmetries taken into account.

The lower-latitude cusp ions originate from the prenoon low-latitude magnetopause, \(z \sim -5\) to \(5\, R_E\). Because of the weak poleward electric field in this region, the ions undergo a moderate \(E \times B\) dawnward drift during their flight from the magnetopause to the ionosphere. This results in a dispersionless cusp, in sharp contrast to the classical southward IMF cusp. Because of the \(E \times B\) dawnward drift, the dispersion occurs in the east–west rather than the north–south direction, which is harder to observe from a typical polar-orbiting satellite that traverses along a meridian such as DMSP.

The lower-latitude dispersionless cusp perhaps falls under the category of stagnant or weak IMF \(B_z\) cusp in the cusp classification scheme developed by Yamauchi and Lundin [1994]. In their study, which sorts the cusp by IMF \(B_z\), their stagnant cusps occur most frequently during periods of weak IMF \(B_z\). With a weak z component, the IMF orientation may be dominated by the y component. If this is the case, then their result can be explained in terms of merging locations and weak and/or dawnward/duskward \(E \times B\) discussed here. The present study shows that, in addition to IMF \(B_z\), IMF \(B_y\) plays an equally important role in determining the cusp morphology.

The higher-latitude cusp ions originate from higher-latitude magnetopause regions \((z \sim 7\) to \(13\, R_E\)) at prenoon to noon or slightly postnoon. Once the ions enter the magnetosphere, they undergo strong \(E \times B\) dawnward and poleward drift. The lower-energy cusp ions originate from postnoon, whereas the higher-energy ions, from the prenoon magnetopause. Because of a significant poleward drift, the dispersion of the higher-latitude cusp ions has some resemblance to that of the classical southward IMF cusp ion dispersion.

It should be noted that the model double-cusp event is located near noon or slightly prenoon. This result does not contradict the previous statistical studies of the local time effect of IMF \(B_y\), which report that the center of the cusp shifts duskward (dawnward) in the Northern Hemisphere for positive (negative) IMF \(B_y\) [e.g., Newell et al., 1989; Zhou et al., 2000]. The postnoon cusp particles would originate at locations further duskward than the entry points of the higher-latitude cusp (of the double cusp) ions in Plate 4.

A large proportion of the mantle ions originate from the postnoon magnetopause, \(z \sim -10\, R_E\), and then \(E \times B\) drift dawnward and poleward before precipitating near noon. The poleward drift increases with increasing latitude, as can be seen in Figure 2. Because of the strong poleward convection, the mantle acquires dispersion that has strong resemblance to that of the classical southward IMF mantle.

The locations of the entry points of the lower- and higher-latitude cusps of the model double cusp suggest that merging simultaneously occurs at low- and high-latitude magnetopause during periods of large \(|IMF_{B_z}|\) and small IMF \(B_z\). A satellite traveling in the meridional direction near noon encounters ions from two magnetopause sources. The first is associated with the field lines that have recently merged at low latitude near the noon meridian, and the second, with the field lines that have recently merged at high-latitude and then convect azimuthally toward noon in the manner described above. Weiss et al. [1995] presented a schematic diagram for a similar scenario.
for the case of large IMF $B_x$ and small positive IMF $B_z$, although they did not present any double-cusp observations. This is shown in Figure 7 (adapted from Figure 5 of Weiss et al. [1995]). They suggested that with two simultaneous merging sites, it is possible for an ionospheric satellite to observe discontinuous ion dispersions and ions from two magnetosheath sources even in the presence of steady IMF. The results of our study suggest that two simultaneous merging sites are also possible for the case of large |IMF $B_x$| and small negative IMF $B_z$. Merging at low latitudes during periods of nonsouthward IMF orientation has been previously reported. For example, observations in the vicinity of the magnetopause indicated that in the vicinity of the subsolar region merging occurs at moderate magnetic shear, ranging from 60° to 80°, but at high latitudes merging occurs when the magnetic shear is larger, >135° [e.g., Gosling et al., 1990, 1991]. A recent cusp study reported simultaneous merging at both low and high latitudes during periods of northward IMF [e.g., Fuselier et al., 2000].

Our case study shows that at times the latitudinal separation of the two cusps in the double-cusp event narrows to the point of giving the impression of just one cusp with extended latitudinal width. This may result from several factors, e.g., the seasonal variation which changes the latitudinal locations of the northern and southern merging sites, satellite trajectories, etc. [e.g., Rodger et al., 2000; Weiss et al., 1995]. Forty cusp events were selected from the DMSP 1985–1995 database during periods of large (positive or negative) IMF $B_x$ and small negative IMF $B_z$. It turns out that 30 (75%) of these events are double cusps or cusps with extended latitudinal width. The widening of the cusp latitudinal width when IMF $B_x$ increases in magnitude is corroborated in our statistical study. The study shows that the cusp latitudinal width (clw) = $-0.06 \pm 0.004$ IMF $B_x + 0.5^\circ \pm 0.02^\circ$ and clw = $0.04 \pm 0.02$ IMF $B_x + 0.5^\circ \pm 0.1^\circ$ for IMF $B_x < 0$ and IMF $B_x > 0$, respectively. The scatter is large, which may be partly due to the misclassification of cusps having low-energy flux as open-field line LLBL as well as other factors not considered in this study, such as dipole tilt, etc. Also, the usage of the hourly averaged IMF may contribute to the noise.

Our statistical study confirms the previous results which show that the cusp location moves poleward with increasing IMF $B_x$ during periods of southward IMF. The statistical cusp equatorward boundary (ceb) values obtained in this study are $ceb = 0.78 \pm 0.03$ IMF $B_x + 77.3^\circ \pm 0.1^\circ$ and $ceb = 6 \times 10^{-4} \pm 0.04$ IMF $B_x + 77.9^\circ \pm 0.1^\circ$ for southward and northward IMF, respectively. This result is in good agreement with previous results [e.g., Newell et al., 1989]. However, when the events with large |IMF $B_x$| are removed from the data, the cusp equatorward boundary shifts poleward, and the slope increases slightly; $ceb = 0.81 \pm 0.05$ IMF $B_x + 77.7^\circ \pm 0.2^\circ$ and $ceb = 0.04 \pm 0.06$ IMF $B_x + 78.1^\circ \pm 0.2^\circ$ for southward and northward IMF, respectively. The poleward shift is negligible when IMF $B_x$ is strongly negative, but it can increase up to 0.4° in latitude as the magnitude of $B_x$ decreases to 0 nT. The cusp equatorward boundary moves to lower latitude with increasing |IMF $B_x$|. Taken together, this result and the poleward shift of ceb when large |IMF $B_x$| events are removed, a rather strong case can be made for the cusp equatorward boundary movement to lower latitude with increasing |IMF $B_x$|. This picture is also fairly consistent with our model results. For example, the equatorward boundary of the lower-latitude cusp of the double cusp has lower latitude than that of weakly southward and weakly dawnward IMF cusp, e.g., from Plates 3a and 4. In contrast to the IMF $B_x$ and $B_z$ cases, the cusp equatorward boundary appears to remain relatively constant during periods of northward IMF.

The present study shows that the processes that lead to the creation of the particle cusp are complex, even for those that occur in quasi-steady state. The traditional view of one quasi-steady particle cusp per magnetic cusp (exterior cusp) per hemisphere needs to be modified. While the magnetic cusp produces field line geometry conducive for the formation of the particle cusp, the particle cusp morphology and formation depend on many other factors such as the merging sites, evolution of the magnetosheath plasma and merged field lines, acceleration at the magnetopause crossing, etc.

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P. T. Newell, J. M. Ruohoniemi, and S. Wing, The Johns Hopkins University Applied Physics Laboratory, 1100 Johns Hopkins Road, Laurel, MD 20723-6099. (patrick.newell@jhuapl.edu; mike.ruohoniemi@jhuapl.edu; simon.wing@jhuapl.edu)

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